SPECIAL TOPIC
Coseismic Deformation and Rupture Processes of the 2013 Lushan Earthquake

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The Lushan M_S7.0 earthquake and activity of the southern segment of the Longmenshan fault zone

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Following the Lushan M_S7.0 earthquake on 20 April 2013, a topic of much concern is whether events of M_S7 or greater could occur again on the southern segment of the Longmenshan fault zone. In providing evidence to answer this question, this work analyzes the tectonic relationship between the Lushan event and the 2008 Wenchuan earthquake and the rupture history of the southern segment of the Longmenshan fault zone, through field investigations of active tectonics and paleoearthquake research, and our preliminary conclusions are as follows. The activity of the southern segment of the Longmenshan fault zone is much different to that of its central section, and the late Quaternary activity has propagated forward to the basin in the east. The seismogenic structure of the 2008 Wenchuan earthquake is the central-fore-range fault system, whereas that of the 2013 Lushan event is attributed to the fore-range-range-front fault system, rather than the central fault. The southern segment of the Longmenshan fault zone becomes wider towards the south with an increasing number of secondary faults, of which the individual faults exhibit much weaker surface activity. Therefore, this section is not as capable of generating a major earthquake as is the central segment. It is most likely that the 2013 earthquake fills the seismic gap around Lushan on the southern segment of the Longmenshan fault zone.

Lushan earthquake, Wenchuan earthquake, Longmenshan fault zone, active tectonics, paleoearthquake

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On 20 April, 2013 a magnitude M_S7.0 earthquake struck Lushan, Sichuan Province, killing nearly 200 people and damaging many buildings. To date, no visible coseismic rupture of this event has been found on the surface (http://www.ies.ac.cn). Its epicenter (103.0°E, 30.3°N) lies nearby the Dachuan-Shuangshi fault, which is the southern segment of the Longmenshan fault zone (Figure 1). Focal mechanism solutions and inversions suggest that the source rupture strike was in the NNE-NE direction, dipping to the NW at an angle of 33°–46° as thrust faulting, predominantly propagating towards the southwest (http://earthquake.usgs.gov/earthquakes/eqarchives/fm/neic_b000gcdd_wmt.php, http://www.igg.cas.cn/xwzx/zhxw/201304/t20130420_3823903.html, http://www.cea-igp.ac.cn/tpxw/266824.shtml, http://www.eq-igl.ac.cn). The aftershock distribution and long axis of the meizoseismal area coincide roughly with the Longmenshan fault zone. Between 2008 and 2013, the Wenchuan M_S8.0 and Lushan M_S7.0 earthquakes occurred successively within nearly 5 years of each other on this fault zone. Thus, it is of great concern whether the Lushan event was an aftershock of the Wenchuan earthquake or a contagion [1], and whether a shock of M_S7 or greater could occur again on the southern Longmenshan fault zone (e.g. http://news.sina.com.cn/c/2013-04-21/033926894378.shtml, http://sichuan.scol.com.cn/fffy/content/2013-04/21/content_5064071.htm?node=894, http://society.people.com.cn/n/2013/0424/c1008-21267571.html). There have been few studies on the activity of the southern segment of the Longmenshan fault zone, which in itself is a controversial issue [2–5]. Following the 2008 Wenchuan event, we investigated late Quaternary activity of several major faults of the southern Longmenshan at the request of the Ya'an Bureau of Earthquake Prevention and

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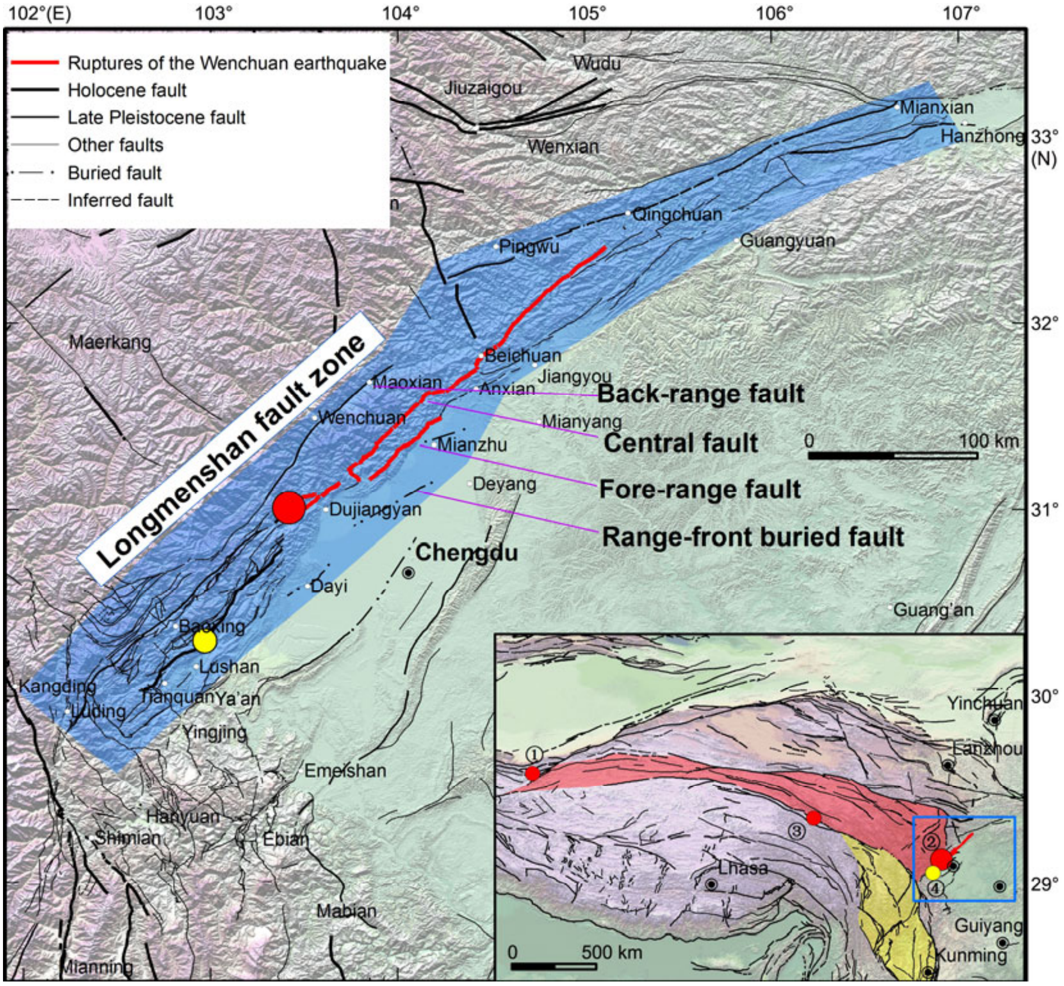

Figure 1 Map showing Longmenshan fault zone and epicenters of recent major earthquakes. ① Yutian, Xinjiang M_S7.3 of 20 March 2008; ② Wenchuan, Sichuan M_S8.0 of 12 May 2008; ③ Yushu, Qinghai M_S7.1 of 14 April 2010; ④ Lushan, Sihchuan M_S7.0 of 20 April 2013.

Disaster Reduction. Based on the results from that work, this paper attempts to further the analysis on the activity and seismicity of the southern Longmenshan fault zone, focusing on the active tectonics and paleoearthquakes. Thus, we hope to provide evidence for answering the aforementioned questions.

1 Tectonic setting

Because of the effect of the northward subduction of the Indian plate, the entire Tibetan plateau is being uplifted steadily and extruded towards the north and east. Consequently, the Bayan Har block is an intensely active secondary block in the plateau, around which at least 10 or more $M_S \geqslant 7$ earthquakes have occurred since the 20th century [6,7]. With the eastward expansion of the Tibetan plateau, this sub-block is being pushed forward and hampered by the large-scale stable South China block, and in between is the Longmenshan thrust-nappe tectonic zone, which consists of a few imbricated faults, such as the back-range, central, fore-range, and range-front (buried) faults (Figure 1). Both the 2008 Wenchuan M_S8.0 and the 2013 Lushan M_S7.0 shocks occurred on the Longmenshan fault zone. The seismogenic structure of the Wenchuan event can be explained by a multiple-unit combination model [8–12], which ruptured simultaneously the three ~12-km-distant faults of the Longmenshan: the Beichuan-Yingxiu (central) fault, the Penguan (fore-range) fault, and the Xiaoyudong fault, which have rupture lengths (and nature) of >200 km (thrust-reverse right-slip), >70 km (thrust), and ~7 km (thrust left-slip), respectively [9–14]. In addition, slight damage was seen on buried faults around Mianzhu [15]. Following the Wenchuan earthquake, trenches excavated along the surface rupture belt revealed paleoearthquakes similar to the 2008 event in coseismic offset on the three aforementioned faults [16–19]. Further south, the Longmenshan fault zone sprays into a series of sub-parallel fault clusters without visible trace on the surface. Near Baoxing, this fault zone begins to intersect the NW-trending faults and diverges further to the NW and SE in a brush shape with an increasing width of up to ~80 km.

2 Late Quaternary activity of southern segment of Longmenshan fault zone

The southern Longmenshan tectonic zone exhibits characteristics of moderate and high mountains with few Quaternary basins and strata. There are many sub-parallel NE-striking faults and arc-like thrust faults (Figure 2) with clear local linear features visible on satellite images of the area.

The southern portion of the back-range fault, also named the Gengda-Longdong fault, begins at Gengda in the north, extends southwards, and sprays into many branches in the area southwest of Wulong. It passes Yaoqi and Longdong, then southwest of Longdong it turns to the NW. There is no obvious expression of active geomorphology along this fault, nor any trace of direct offset on the Quaternary cross sections. In some places, such as Yaoqi and Longdong, sections of bedrock on either side of gullies reveal faults that run through the T1–T2 terraces of streams and show no visible signs of displacement, suggesting little activity of these faults since the formation of the T2 terrace.

The southern portion of the central fault, or the Yanjin-Wulong fault, starts from the south of Yingxiu in the north, stretching southwards past Yanjin, Wulong, and Mingli to the east of Luding, and is composed of many sub-parallel secondary faults. Generally, it trends in the NE (40°) direction, dipping NW with a length of ~160 km. On satellite images, this fault can be identified by linear traces [16]. Investigations of the geology and geomorphology indicate that the Quaternary active main part of this fault should be along the line of Yanjin, Yaside-Mingzhi, Dachigou, Minghe

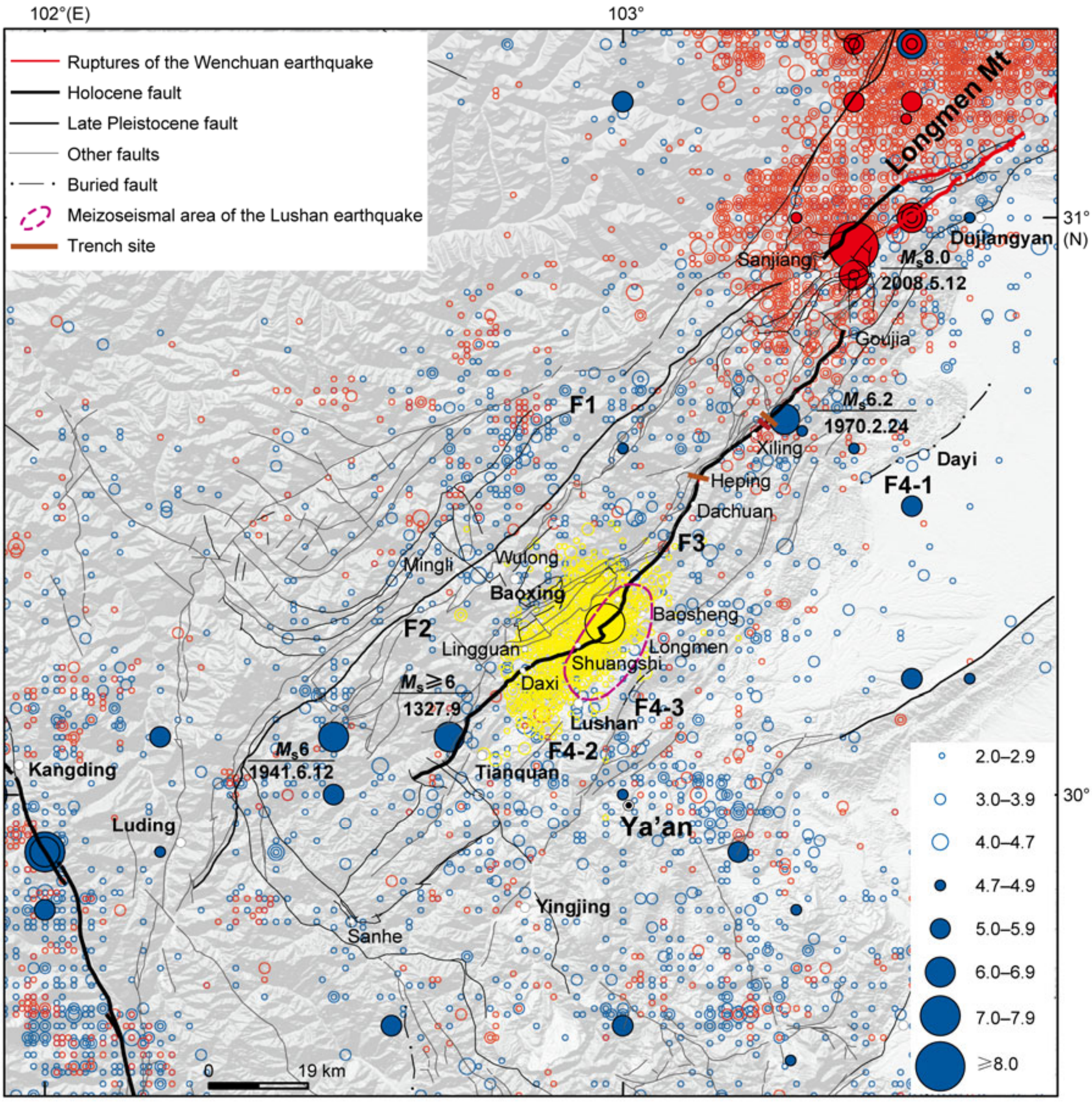

Figure 2 Map showing surface faults of southern Longmen Mt. and epicenters of earthquakes. Blue, events before 2008 Wenchuan M_S8; red, events after 2008 Wenchuan M_S8 and prior to 2013 Lushan M_S7; yellow, events after 2013 Lushan M_S7; solid circle, M_S≥4.7 since 1970; open circle, M_S<4.7 since 1970. Fault names: F1, Gengda-Longdong; F2, Yanjin-Wulong; F3, Dachuan-Shuangshi; F4-1, Dayi; F4-2, Shiyang; F4-3, Xinkaidian.

Village, Mingli, and Zhuangzi Village, south. It is only near Wulong where a direct offset is observed on a Quaternary strata section. Thermoluminescence dating suggests that the flood deposits of 90 ka BP are displaced and are overlain by gray-black clay beds from 78.5 ka BP [3]. Around this section, a wealth of landslides is present at the front of the T3 terrace, nearly 200 m high relative to the river. These landslides are distributed linearly along the fault with possible troughs and valleys, probably implying fault activity after the formation of the T3 terrace. However, at the location where the fault runs through the T1 terrace, there is no visible deformation (Figure 3). We infer that the latest activity of the southern central fault would have been in the early late Pleistocene.

The southern portion of the fore-range fault, or Dachuan-Shuangshi fault, runs from the northeast of Dayi in the north, extending southwards into Ya'an around the north of Heping village, by Dachuan, Taiping, and Shuangshi to the southwest of Tianquan, exhibiting a general strike of NE (40°), dipping NW, and is ~140 km long. Around Shuanghe, a 1-km-long linear trough is present that can be recognized on satellite images. This trough extends discontinuously to the south with linear geomorphic expressions on the surface. Prior to the Wenchuan earthquake, Densmore et al. [4] excavated a trench in this trough near Qingshiping, Shuanghe and found two paleoearthquakes on the fault, of which the latest occurred between 930±40 and 860±40 a BP. Following the 2008 event, Dong et al.[1)] performed another excavation across this trough near the former trench and revealed a paleoearthquake in 1390–650 a BP with displacement of ~0.3 m (Figure 4). We also excavated a trench at Heping Village, Dachuan (103°07′54.03″E, 30°32′51.999″N). The cross section of this new trench shows that to the west of the broken zone, the muddy mark beds bearing gray-green gravel masses, which formed in a quiet-water depositional environment, tilt intensely. On either side, but particularly on the west side, gravel is remarkably oriented (Figure 5), reflecting fault displacement. The two ^{14}C dating results of the

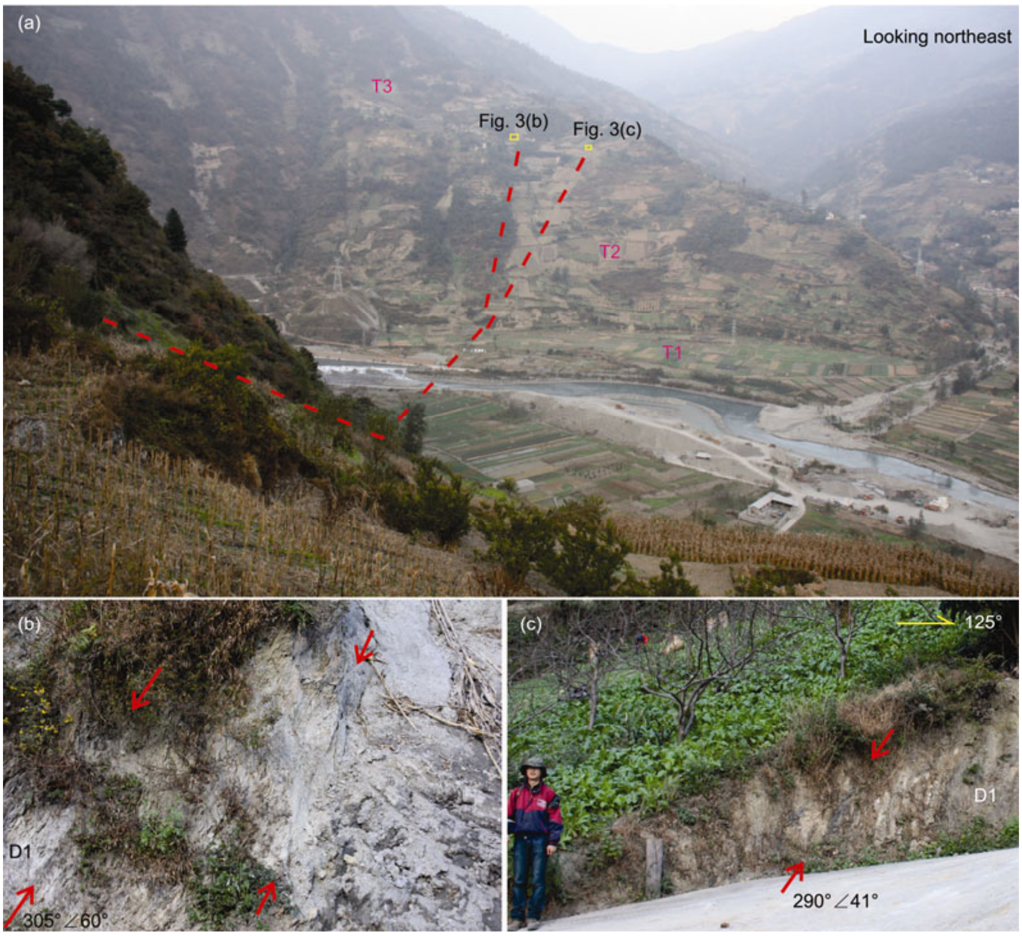

Figure 3 (a) Photograph showing the fault and landforms series. Red dashed line is the position the fault runs through; T1–T3, terraces. (b) and (c) Two exposed fault sections on the left bank of Wulong River. Red arrow denotes fault plane; D1, shale and quartz sandstone of Lower Devonian.

1) Institute of Geology, China Earthquake Administration. A report of scientific investigations on the Wenchuan *M*8.0 earthquake: Recurrence intervals of major earthquakes on the Longmenshan fault zone. 2009

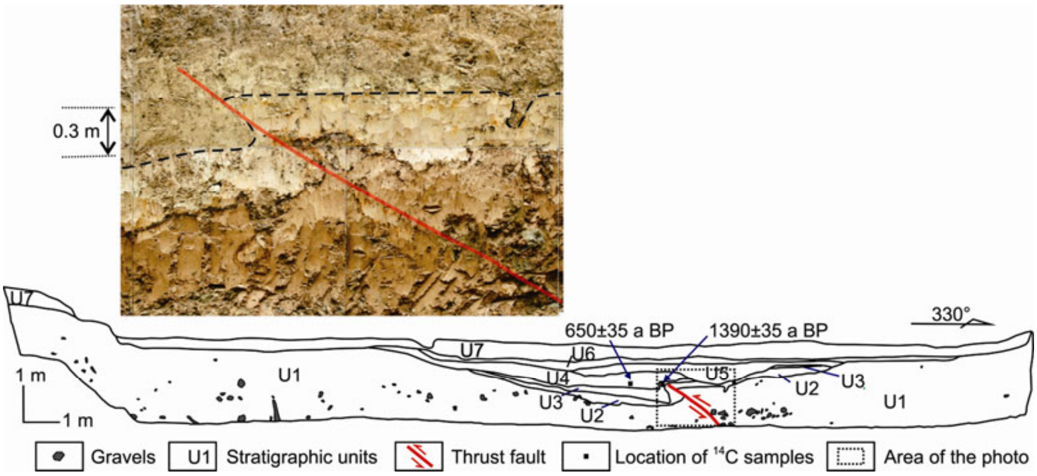

Figure 4 Trench section nearby Qingshiping Village (103°14′48.2″E, 30°38′43.8″N) on the Dachuan-Shuangshi fault. U1, Brown clay with scattered gravels; U2, light brown clay; U3, yellow-green clay; U4, gray silt clay; U5, reddish-brown or yellowish-brown clay with few tiles; U6, gray man-made deposits; U7, dark soil for farming. From Dong et al.[2)] with minor corrections.

mark beds are all 330±30 a BP. At the location where the fault runs through the T1 terrace, there is no trace of deformation. The sample from the bottom of the trench was dated at 120±30 a BP. With OxCal software, correction constraints were imposed on the sample age, yielding Cal AD 1840–1890 for the time of the event. In addition, as seen on the fault section at Daxi Village, south of Lingguan Town, Baoxin County, the fault offsets the late Quaternary lake strata, which were dated as 57.4 ka BP by the TL method and it produced a 2-m-high scarp [3]. These sections all demonstrate that the fault offsets the Holocene strata, but that the displacement for one event is merely ~0.3 m and the fault plane is not very clear. Only a few researchers have identified right-slip in light of drainage offsets or landslides, and no other visible horizontal strike-slip has been observed along the fault.

The southern portion of the range-front fault, or Dayi fault in a general sense, stretches roughly along Dayi, Shuikou, and west of Mingshan and Yingjing. It comprises many branches that are not continuous on the surface, such as the Dayi fault in a narrow sense, Shiyang fault, and Xinkaidian fault (Figure 2). The narrow-sense Dayi fault is hidden at a depth beneath the east flank of the Dayi anticline [20], along which no offset of late Pleistocene to Holocene has been found on the surface, but where some traces of active folding are present. Thus, the inference is that this is a blind fault, active since the late Pleistocene and not reaching the surface [21]. Furthermore, the Shiyang and Xinkaidian faults, both lie in the 8 degree seismic region of the 2013 Lushan event, and no trace of activity in the late Quaternary has been observed.

3 Historical earthquakes and paleoearthquakes

On the southern Longmenshan fault zone, there have been three documented M_S>6 earthquakes: the 1327 Tianquan $M_S \geqslant 6$, the 1941 Luding-Tianquan M_S6, and the 1970 Dayi $M_S6.2$ (Figure 2). Because of the war, there is little description of the 1327 Tianquan quake, which might have been as strong as $M_S7^1/_2$–$7^3/_4$, based on the area of devastation and greatest felt distance when compared with the 1786 south Kangding $M_S7^3/_4$ quake [22]. The instrumental epicenter of the 1941 M_S6 quake was located between Luding and Tainquan, which caused serious damage in Kangding, Luding, and Baoxing [22–23]. The source rupture of the 1970 Dayi $M_S6.2$ strikes in the NE (65°) direction, dipping NW at 50° with intensity 7 degree at the epicenter. A NE-NEE directed meizoseismal area around Changshiba, Dachuan of Lushan to Dafeishui, Shuanghe of Dayi [23], and 50 or more aftershocks followed within 10 days of the main shock [24].

Several trenches have been excavated on the Heping-Qingshiping segment of the Dachuan-Shuangshi fault, which revealed evidence of at least one or more paleoearthquakes since 1000 a BP, although their offsets and shock traces on the ground are not very typical. This area is within the meizoseismal area of the 1970 Dayi $M_S6.2$ event, but no trace of this quake was found in these trenches; implying perhaps that this event was smaller in magnitude than the paleoearthquakes. Furthermore, considering the phenomena discovered in the trenches and ~0.3-m coseismic displacement, we estimate that the paleoearthquakes on the Dachuan-Shuangshi fault were of moderate magnitude.

2) Same as on page 3478.

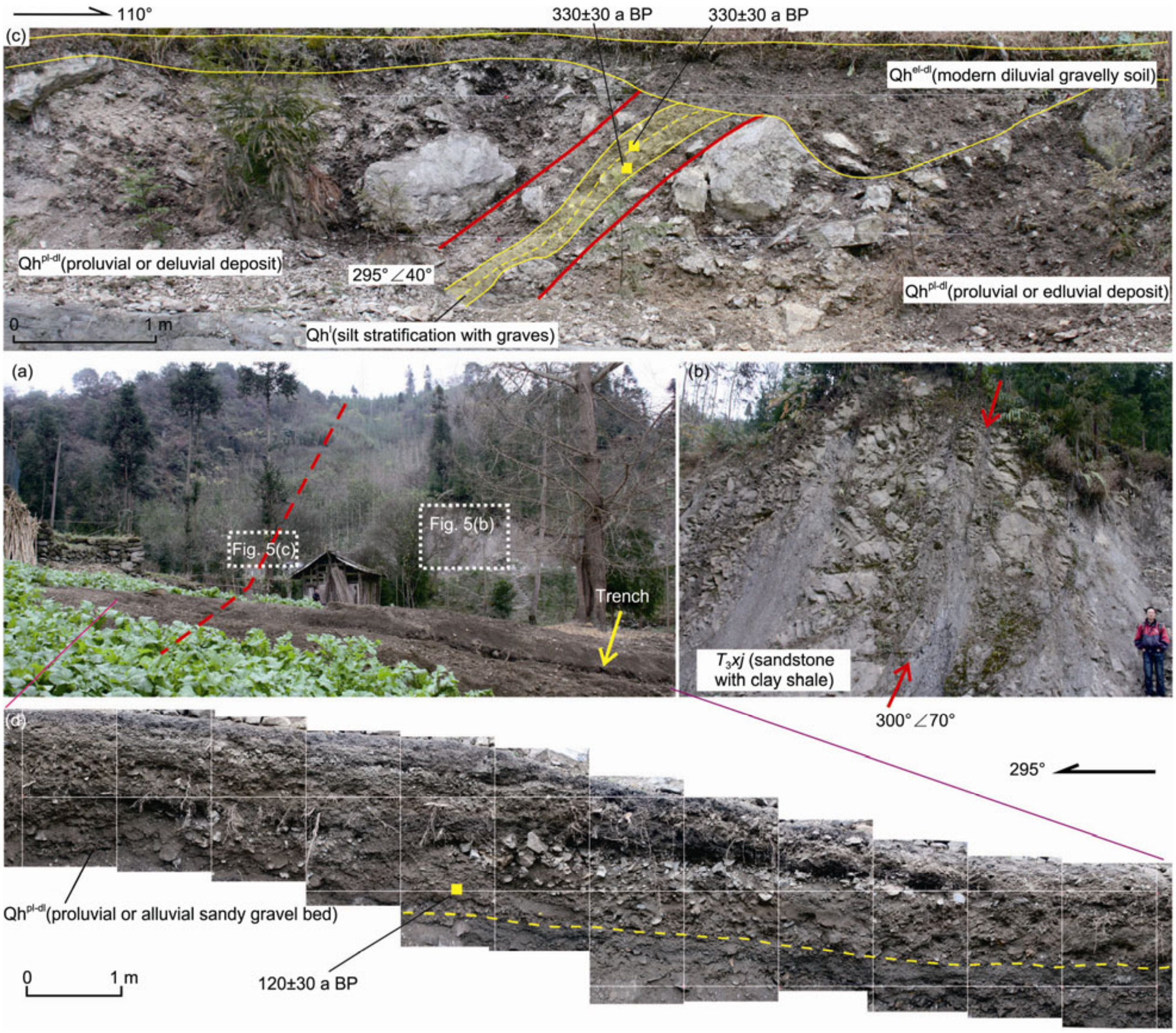

Figure 5 Trench section nearby Heping Village (103°07′54.0″E, 30°32′52.0″N) on the Dachuan-Shuangshi fault. (a) Location of trench and section; (b) fault plane in bedrock; (c) cleaned trench section; (d) excavated trench section. Red lines refer to fault plane, between red lines is orientated zone of muddy beds and gravel, yellow lines denote stratum boundary, yellow dashed line means stratification, yellow rectangle is location of AMS sampling and dating result, yellow shadow is mark layer, red arrow is directed to fault plane.

4 Discussion

Investigations show that the southern and central segments of the Longmenshan fault zone differ conspicuously in their activity, in that late Quaternary activity has probably spread towards the basin in the east. In the central segment, the central fault has the largest scale and most profound trace of activity, followed by the fore-range fault. In the southern segment, only the fore-range fault exhibits weak activity in the Holocene, and the Dayi fault is likely a developing hidden fault. The 2008 Wenchuan earthquake produced surface ruptures along the central fault and fore-range fault, and its aftershocks were concentrated along the central fault and its west side (Figure 2). However, the 2013 Lushan M_S7.0 event did not generate visible ruptures on the ground, which is likely associated with the fore-range fault or the range-front fault further to the east, as inferred from focal mechanism, source process inversion, and damage distribution. With the Lushan quake, the aftershocks are confined to the fore-range fault and not linked to that of the Wenchuan event (Figure 2). This implies that the Wenchuan and Lushan quakes did not result from the same source rupturing. The source of the Wenchuan event is the central-fore-range fault system, whereas that of the Lushan quake needs further investigation, although it is primarily related with the fore-range-range-front fault system, but without clear relation to the central fault. The magnetotelluric sounding profiles also reveal different deep structures beneath the two earthquake areas, i.e. low-resistivity bodies are present in the high-resistivity zone beneath the Wenchuan, whereas no such feature was detected below the Lushan [25].

The southern segment of the Longmenshan fault zone has a greater width and a greater number of secondary faults, of which the activity of individual faults is much weaker than that of the central segment of the Longmenshan. On the central fault and fore-range fault of the central section, there are many active landforms and well-preserved paleoearthquake traces have been found at many places with coseismic displacement >1 m for single events [16–19]. On the southern section, scattered active traces of Holocene and paleoearthquakes are observed only on the Dachuan-Shuangshi fault with atypical offsets, ~0.3-m displacement for one event. Although some researchers contend that the Dachuan-Shuangshi fault has right-slip [4,5], their evidence is only from offsets in drainage channels or landslides at single localities. On the other hand, the focal mechanism solutions indicate that the Lushan event is one of thrust faultings. From a structural comparison, the capability to generate earthquakes on the southern segment of the Longmenshan fault zone is weaker than that of the central segment of the Longmenshan.

Recent studies suggest that the seismic gap on active faults is an important indicator for earthquake hazards [26–28]. On the southern segment of the Longmenshan fault zone, there is a nearly 40-km-long seismic gap between the Wenchuan and Lushan earthquakes (or longer if measured along the fore-range fault) and a 70-km-long gap is also present south of the Lushan earthquake; both seem to imply future seismic risk. However, in the longer view, at least one M_S6.5–7.0 shock has occurred since 1000 a BP between north Dachuan and Wenchuan, a magnitude 6.2 quake took place at Dayi in 1970, and also other smaller earthquakes happened there (Figure 2). Consequently, it is probable that this section is no longer a seismic gap. From south of the Lushan to the Xianshuihe-Anninghe fault zone in the south, the 1327 Tainquan $M_S \geqslant 6$ and 1941 Luding-Tainquan M_S6 quakes took place on the southern segment of the Longmenshan fault zone. In other words, the Lushan event seems most likely to fill the pre-existing gap of this earthquake cycle. Of course, this inference needs further supportive evidence from historical and pre-history earthquakes, especially in the area south of Lushan.

5 Conclusions

(1) The activity of the southern segment of the Longmenshan fault zone is much different to that of the central section, where the late Quaternary activity has probably propagated forward to the basin in the east. Even though both the Lushan and Wenchuan events occurred within the same tectonic system, their source is not the same. The Wenchuan shock was generated by the central-fore-range fault system, whereas the Lushan event was associated primarily with the fore-range-range-front fault system, with little relation to the central fault; however, this inference should be verified by further investigations.

(2) The southern segment of the Longmenshan fault zone is wider and has a greater number of secondary faults, of which surface activity of individual faults is considerably weaker. A structural comparison suggests that the southern segment of the Longmenshan fault zone is less capable of generating major earthquakes than is the central section.

(3) This earthquake seems most likely to fill the seismic gap around Lushan on the southern segment of the Longmenshan fault zone.

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